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CLIMATE CHANGE IN BELARUS DERIVED FROM THERMOGRAMS

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Terrestrial temperatures were measured during several years both in shallow and deep boreholes in Belarus mainly for heat flow studies. The thermograms, registered under steady-state conditions in holes within all main tectonic units of the country, have sometimes both concaved and convexed shapes. They have an imprint of the ground surface paleotemperature change. Temperature fluctuations at the ground surface propagate into the ground with attenuated amplitudes and the phase shift, dependent on the depth. A few temperature versus depth diagrams without noticeable influence of ground water circulation were selected for paleoclimatic reconstructions. First estimates show that the ground surface warming 0.5–1 °C took place during the last 200-300 years. The reliability of the climatic signal, derived from thermograms, is dependent on local conditions. For instance, the groundwater circulation, the agricultural effect, resulted from the cultivation of the land, but no detailed information is available both on the history of the agricultural use of the land around studied boreholes and the velocity of water filtration in the vicinity of selected sites.

Introduction

Borehole thermograms represent a combined effect of several parameters, such as heat flow density, thermal properties of rocks, past and present temperature variations at the ground surface, the heat production resulted from a decay of radioactive elements, an advective heat transfer, caused by the groundwater circulation and others. Heat flow values depend on the local geology and reflect thermal conditions of crustal blocks. The transient temperature component, resulted from the ground surface temperature (GST) variations, is superimposed to the temperature diagram. After processing of them the evidence of significant climatic changes was shown by many investigators when analysing thermograms, recorded in different countries (Nielsen and Beck, 1989, Cermak et al., 1991; Pollack and Chapman, 1993; Chapman and Harris, 1993; Beltrami and Taylor, 1995; Stulc et al., 1997). This conclusion was confirmed also by analysis of climatological records, geological and geochemical data, by examining of tree rings, polen diagrams, etc.

Daily and seasonal temperature changes at the ground surface produce its short-period and annual oscillations. At the same time the long-perid ones are the result of many-years and secular weather changes occured in the past. Both of these waves were propagated downward. The lower was the frequency of such fluctuations, the deeper formations they affected and vice versa, the shorter was the temperature wave the shallower horizon it propagated, being exponentially attenuated.

Daily temperature cycles can not produce noticeable influence for horizons deeper than a few dozens of centimetres, or a few metres, depending on thermal properties of rocks and the velocity of ground water circulation in permeable rocks. Long-term (low-frequency) temperature fluctuations at the ground surface propagated with attenuation into deeper horizons, reaching sometimes depths up to 1000-2000 metres. The influence of infiltration is noticeable within recharge areas. It is especially pronounced in a sequence of loose sediments without regional aquitards within the fresh water zone. Therefore, only selected thermograms recorded in boreholes could be used for paleoclimatic reconstructions. As the amplitude of the paleoclimatic signal is significantly attenuated at greater depths, high-reso-lution borehole thermometers are necessary for temperature logging of boreholes reached the thermal equilibrium after their drilling was finished. The deeper the studied borehole, the longer GST history interval could be retrieved.

The area distribution of boreholes, selected for the paleoclimatic reconstruction is shown in Fig.1. One of them the Bulavki 41-pl borehole, located in the north-eastern Belarus in a large tract of the forest a few metres aside a local ground road within the Precambrian Orsha Depression, is considered in details to show some typical features in its upper part. Temperature measurements till the depth of 281m were fulfilled in 1986, July by a thermistor thermometer. A few months elapsed after its drilling was finished and measurements were undertaken. Progressive depth intervals between temperature readings were used: 1m (the depth interval 2-15 m), 2.5 m (15-30 m), and 5m (30-280 m). The intercept of the thermogram to the ground surface gives the temperature below 7 °C Fig. 2, which is determined by the ambient mean annual temperature for this locality and the air-soil heat transfer features. The diagram is close to the linear one within the interval 50-245m. The minimal value 6.35 °C corresponds to the depth of 8 metres and the annual temperature wave reaches the depth of 13 metres, below which it is possible to trace an imprint of attenuated waves of a few previous annual temperature cycles, Fig.3. The diagram for the upper 40 metres is shown in details. The gradient is a function of the depth with the general tendency to decrease till 80-90 m, below which it gradually increases. Such an effect could be the result of thermal properties variation for different layers of sediments, e.g. caused by different mine-ralogic composition, their compaction, or the cooling effect occured in the uppermost part of the geologic sequence. It could be produced by the downward ground water filtration, but this assumption was done on a qualitative level, as the filtration rate was not examined for this borehole, at the same time rock samples were absent to fulfill detailed studies of the thermal conductivity profile. Thermograms for other analysed boreholes have similar features.

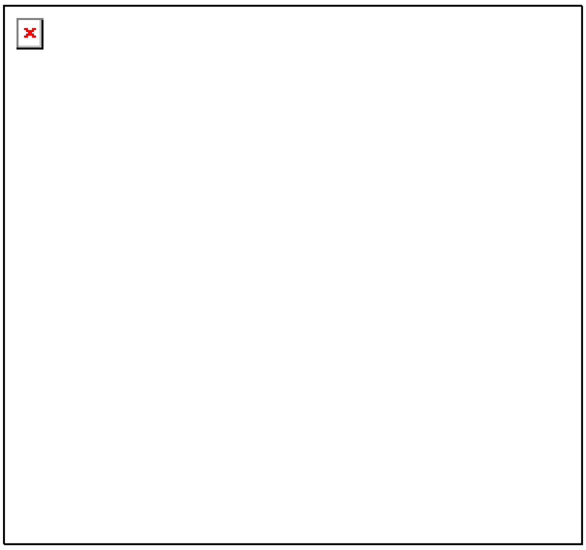

Fig.1. **Position of studied boreholes in Belarus used for the paleoclimatic reconstruction.** Main tectonic units of the area: Belarussian Anteclise (BA), Brest Depression (BD), Baltic Syneclise (BS), Orsha Depression (OD), Pripyat Trough (PT), and the Ukrainian Shield (US). See Table 1 for abbreviations of boreholes.

Рис.1. **Местоположение изучаемых скважин в Беларуси, использованных для палеоклиматической реконструкции.** Основные тектонические структуры региона: Белорусская антеклиза (BA), Брестская впадина (BD), Балтийская синеклиза (BS), Оршанская впадина (OD), Припятский прогиб (PT), Украинский щит (US). Аббревиатура скважин видна из Таблицы 1.

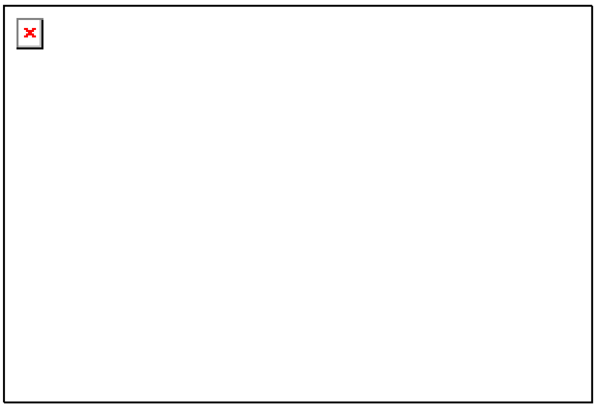

Fig.2. **The upper part of the temperature-depth profile for the borehole Bulavki 41-pl, the Orsha Depression.** Asterisks show points of temperature measurements.

Рис.2. **Верхняя часть термограммы для скважины Булавки 41-пл, Оршанская впадина.** Звёздочками показаны точки измерений.

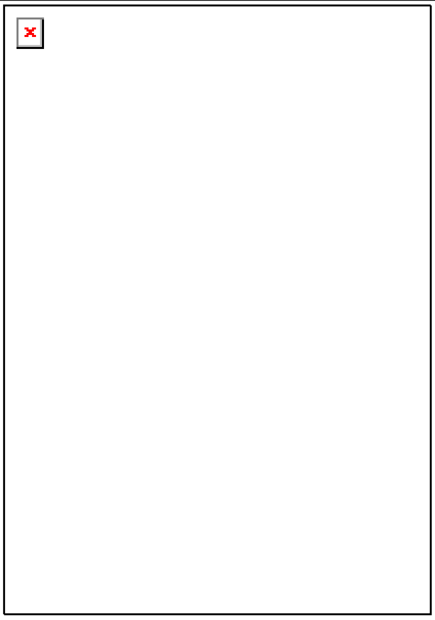

Fig.3. **Temperature gradient for the Bulavki 41-pl borehole.** The upper part of the diagram is superimposed to the main plot in larger scale to show details of the gradient variations.

Рис.3. **Геотермический градиент по скважине Булавки 41-пл.** Верхняя часть диаграммы наложена на основной график, чтобы показать детали изменения градиента.

The approach limits

At present the information on climate variations is available for the Pleistocene interval of time for the territory of Belarus. A paleotemperature reconstruction was fulfilled from the present time to 125 thousand years b.p. It was based on paleoenthomofaunal data together with paleobotanic results of radiocarbon dating (Nazarov, 1984). Temperature smoothed curves for mean annual and mean-July data sets are shown in Fig. 4. After two paleoclimatic optima happened around 120 and 100 thousand years ago there was quite long-time ice age with the mean annual temperature around 11 °C below zero, after which the warming around 14 °C took place (Parkhomov, Kozel, 1993). The curve has rather low short-time resolution especially for the time interval below 11-12 thousand years b.p. when the glacier retreated. It was necessary to seek for other alternative approaches to derive the ground surface temperature (GST) history for a few hundred years ago.

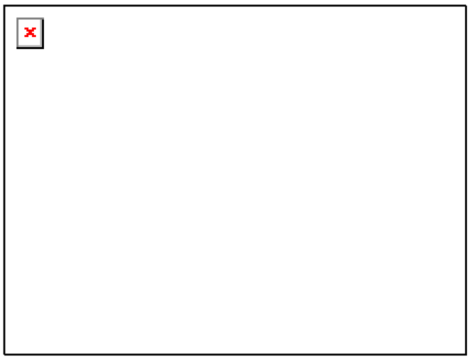

Fig.4. **Ground surface temperature (GST) change during the Late Pleistocene period (simplified) within the territory of Belarus.** 1 - mean annual smoothed curve; 2 - mean July GST (Nazarov, 1984; Parkhomov, Kozel, 1993). The warming happened after the ice sheet retreat.

Рис. 4. **Изменение температуры поверхности Земли (GST) в течение плейстоцена (упрощено) в пределах территории Беларуси.** 1 - среднемноголетняя сглаженная, 2 – средне июльская GST (Назаров, 1984; Пархомов, Козел, 1993). Потепление произошло после отступления ледяного покрова.

The time intervals of available direct meteorological observations usually don't exceed 200 years in Europe and it is possible to judge on climate changes beyond it (200-1000 years) using indirect approaches. Temperature log records in boreholes with imprints of ground surface temperature history are among them. The propagation of temperature wave into the subsoil is rather inertional process. In result, the terrestrial temperature field represents some kind of temperature "memory", which keeps the information on ground surface temperature variations, which could be recovered from thermograms recorded in boreholes. Usually, the precision of temperature measurements, fulfilled by geophysical thermometers in boreholes, ranges from 0.1 to 0.01 ^{O}C. It is believed that the reconstruction of more reliable temperature history up to 1000-2000 years is possible, though longer time intervals up to 13-20 ka were reported (Safanda, Rajver, 1999) for thermograms recorded in boreholes of 1.5-2.5 km deep in Central Europe. For instance, the inversion of a temperature log for the German super-deep KTB borehole indicates the warming 10 ^{O}C occured around 14 ka before present time.

Data

We selected a few temperature versus depth diagrams, recorded in boreholes of Belarus, reached the thermal equilibrium and located within different tectonic units (see Fig. 1) to fulfill preliminary estimates of the ground surface paleoclimatic history in Belarus. Electric thermometers were used for point-by-point temprerature measurements usually with 5, 10 or seldom 20m depth intervals. Rather often the uppermost part of boreholes was measured with intervals 1-2.5 metres. Semiconductor thermistor probes were calibrated using a set of precise mercury-in-glass TP-1 and TP-2 thermometers with divisions 0.01 and 0.02 K. It was believed that the thermistor probe had an accuracy 0.03-0.04 K and the relative resolution around 0.001-0.005 K, respectively. Temperature measurements were undertaken till the depth of a few hundred metres during several field expeditions organized usually at the summer time. A negative temperature gradient was observed in the upper parts of geological sections up to the depths of 10-70 metres depending on the borehole. It indicates transient features, caused by the effect of temperature changes, in particular, annual temperature fluctuations at the ground surface and possible influence of the infiltration into loose near-the-surface rocks, after which the temperature increases monotonously with the depth. In some cases the gradient also gradually increases downwards. Moreover, the additional uncertainty could be produced by different factors distorting the themperature diagram like the contrast of thermal properties within thin-layered sequences of sediments. All thermograms were recorded in holes located in plain areas, therefore we didn't apply topographic corrections.

The geological columns were represented by terrigenous rocks of different age. There was no high conductivity bodies like anhydrides, iron ores or rock salt, encountered in of studied boreholes. In most cases we had no drill core samples to measure thermal properties of rocks for selected boreholes. Usually such measurements were still available for other holes, located in the same area. They didn't show a considerable scatter of heat conductivity coefficients.

Results

After preliminary analysis we selected temperature versus depth diagrams for the paleoclimatic reconstruction recorded in the next boreholes: Brest 9sh, Gomel 42-1, Naroch 101 and 102, Pukhovshchina 27zh, Bulavki 41-pl, Shashki 306, Lakhva 1, Lettsy, Resta with the depth range 200-650 metres (Figs. 5 and 6). They are located within the main tectonic units of Belarus: the Brest and Orsha depressions, the Pripyat Trough and the Belarussian Anteclise (Table 1.). For these boreholes the drilling process was finished at least 1 month before tempe-rature measurements were undertaken. Inner diameters of the casing were typically 70-100 mm, therefore no pronounced influence of spontaneous convective heat transfer within the casing was expected (Kriege, 1939).

Fig. 5. **Temperature - depth diagrams used for paleoclimatic reconstruction (group 1).** No distinct distortions of thermograms are visible.

Рис.5. **Термограммы, использованные для палеоклиматической реконструкции, группа 1.** Отсутствуют видимые искажения на термограммах.

Fig. 6. **Temperature - depth diagrams used for paleoclimatic reconstruction (group 2).** The Lettsy thermogram has slightly concaved form.

Рис.6. **Термограммы, использованные для палеоклиматической реконструкции, группа 2.** Термограмма Летцы имеет слегка вогнутую форму.

Table 1. **Boreholes, used for the paleoclimatic reconstruction in Belarus.**
HFD is heat fllow density, Elapsed time is the time elapsed after the drilling was finished and temperature measurements were undertaken, the local landscape: B = bushes, F = forest, M = meadow, V = river valley

Borehole and tectonic unit	Coordinates		Depth of measurements, m and landscape	Temperature logging date	HFD, mW/m^2	Elapsed time, days
	Lat. N	Lon. E				
Brest 9sh (BD)	52°10.5	23°41.9	215 (B)	June 12. 1986	53	>1500
Bulavki 41-pl OD)	55°35.1	28°46.7	281 (F)	July 14, 1986	~30	>60
Gomel 42-1 (BA)	52°18.1	30°58.1	322 (M)	June 19, 1985	42	>400
Lakhva 1 (OD)	53°46.7	30°07.9	525 (F)	June 13, 1985	30	>180
Lettsy (OD)	55°11.8	29°55.6	510 (V)	July 31, 1984	32	>50
Naroch 101 (BA)	54°54.3	26°49.7	560 (M)	July, 1990	~45	>200
				Nov.,1993		>1400
Naroch 102 (BA)	54°54.3	26°49.7	291 (M)	July 13, 1990	~45	>200
Pukhovshchina 27zh (BA)	53°30.2	27°58.7	640 (M)	June 6, 1984	16	>40
Resta 1 & 2 (OD)	53°49.9	30°41.3	500 (F)	June 15, 1985	40	>120
Shashki 306 (BA)	53°39	26°49	522 (M)	June 11, 1984	~30	>30
Vost.-Vystupovichi 2 (PT)	51°37.2	29°00.8	3350 (F)	July 2, 1977	44	>550

Note: The *tilda* symbol in the HFD column indicates that the calculated heat flow density from nearest boreholes was accepted, as its determination was not available for the studied borehole.

It was believed that it is possible to neglect the large-scale water flow effects in rocks, surrounding each borehole, though some local perturbing phenomena could be possible, but there was no special hydrogeological investigations undertakren to estimate their scope. The water table in metallic casing pipes typically was at the depth of 5-20 metres and the temperature measurements were not fulfilled within the air-filled interval in boreholes. The range of extrapolated surface temperature values for thermograms varies from 6.7-7.2 in the northern Belarus to 8.0-8.3°C in the southern and south-western part of the country. Generally it is lower for boreholes drilled in a forest in comparison to a field. All thermograms have no distinct indications of distortions caused by surface factors. Taking into account the lack of thermal properties of rocks for these boreholes it was necessary to use one of simple methods to recover the ground surface paleotemperature history. We selected the approach and related inversion program developped by Dr. P. Shen (Shen, Beck, 1991; Shen, Beck, 1992). The program allowed to process thermograms when the detailed information on thermal properties of sediments was incomplete, or it was absent entirely, which took place in our case.

In most cases the processed thermograms show 2-3 temperature minima and maxima (Fig. 7). One of them is in the range 1350-1450 years and the second one lies in a wide interval from 1880 to 1950 years for the boreholes located within the Brest and Orsha depressions, as well as within the Belarussian Anteclise. According to the results of calculations the tendency of the ground surface temperature to increasewas observed after forties-fifties years of the current century. Evidently, some of selected shallow holes, especially drilled within positive crustal units, could not be considered as reliable sources of the information. In particular, due to a possible influence of the advection, caused by ground water circulation especially within the fresh water zone intervals, the used inversion program doesn't include the analysis of such effects. Usually, calculations indicate a small decrease in temperature within the time span 1900-1950 years. Model results for a number of deep boreholes reveal one temperature minimum in the range 1700-1800 years and the second one corresponding to fifties-seventies years of the current century.

Discussion

Poozerian (Valdaian, Würmian) glaciation with the duration around 85 thousand years (ca. 95,000-10,000 years b.p.). was the last one within the territory of Belarus. It was one of the coldest glaciations during the whole Anthropogene period (Gealogiya, 1983). The area covered by the glacier coincides approximately with the Poozerie, the northern part of Belarus. Briefly the temperature conditions were following, rather short preboreal period (10200-9500 y.b.p.) was characterized by cool, continental climate within the territory of Belarus (Bogdel, 1981). During the Boreal period (9500-8000 y.b.p.) the climate became warmer, the Atlantic period (8000- 5000 y.b.p.) was a climatic optimum with a warm and humid climate. Increased mean year temperatures were typical for the sub-Boreal time (5000-2200 y.b.p.) followed by the sub-Atlantic period, the last period of Holocene started since 2200 y.b.p. Some temperature reduction and the humidity increase was typical for it. During it narural forests and verdure areas were changed due to the considerable human activity, Clearing forests, agricultural cultivating formerly unused lands, development of pastures for a cattle and became more frequent charred tree-trunks after forest fires, etc., changed the existed natural vegetation cover. Woodless plains appeared progressively in different parts of the territory. At present only around 30 percent of Belarus is covered by forests. Therefore, the vegetation undergo sufficient changes during the Holocene. Predominated forest associations were undergoing the permanent change depending on the relief and soils. The role of technogenous factor continues to increase until the present time. Therefore, the climate was partly determined by the vegetation cover and the human activity.

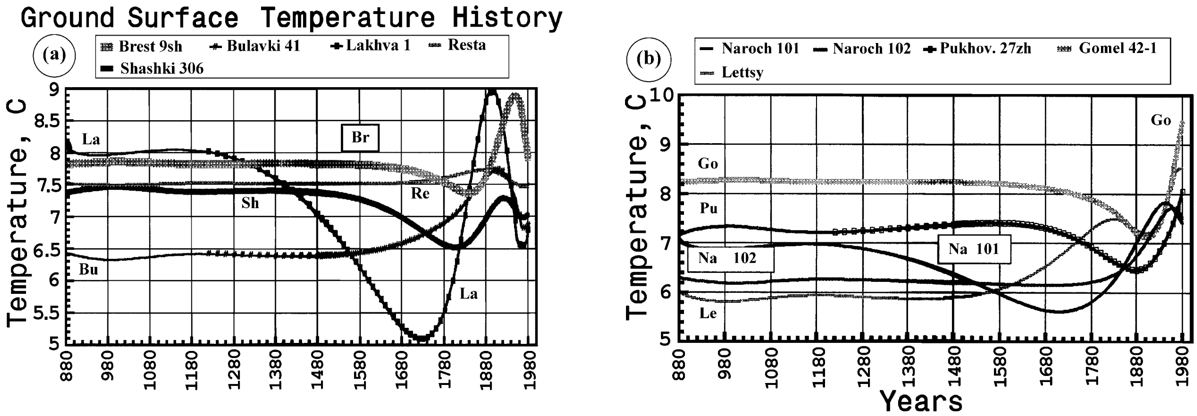

Fig.7. **Ground surface temperature (GST) changes within Belarus inferred from thermograms recorded in different boreholes attained the temperature equilibrium after their drilling was finished.** The plots (a) and (b) represent different groups of boreholes.

Рис.7. **Изменения температуры поверхности Земли (GST) в пределах Беларуси, полученные из термограмм, зарегистрированных в разных скважинах, достигших теплового равновесия после завершения их бурения.** Графики (a) и (b) представляют разные группы скважин.

Researchers reported a global warming during the current century from different continents. It was accompanied by the increase of greenhouse gases supplied to the planet atmosphere. The instrumental observations of the climate change in Belarus are available since 1881 with temperature records in the time span 15-115 years, but only a few stations have such records during more than 100 years, e.g. Minsk, Gorki, Maryina Gorka, Vitebsk, Brest (Klimat, 1996). The mean annual temperature increased for around 1 K since 1881 (Fig. 8) at the background of sufficient scatter of its values for each year. Rapid changes around 0.7 K happened since the end of seventies with the tendency for the mean temperature to increase, which is in agreement with our calculations for the most of individual boreholes, though there are sometimes disagreement, not completely understood. One of such examples could be the attempt to reconstruct paleoclimatic history for borehole East-Vystupovichi-2 (Fig. 9). The hole is located within the southern part of the Pripyat Depression near the South-Pripyat Fault, separated it from the Ukrainian Shield. A long-time climate warming from around 1200 till 1800 years looks like not realistic. One of possible distorting effects could be not enough time elapsed between the drilling was finished and temperature measurements were undertaken, another reason could be a deep-penetrating ground water filtration cooling the upper 500-1000 m of the geologic section. As it was mentioned the used inversion program didn't take it into account.

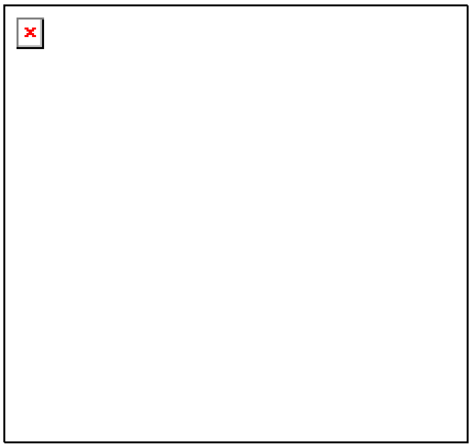

Fig. 8. T**he mean annual temperature variations recorded by Belarussian meteorologic stations.** Dots indicate values for different years (Klimat, 1996), modified.

Рис. 8. **Среднегодовые вариации температуры, зарегистрированные метеорологическими станциями Беларуси.** Точками показаны значения для отдельных лет (Климат..., 1996), с изменениями.

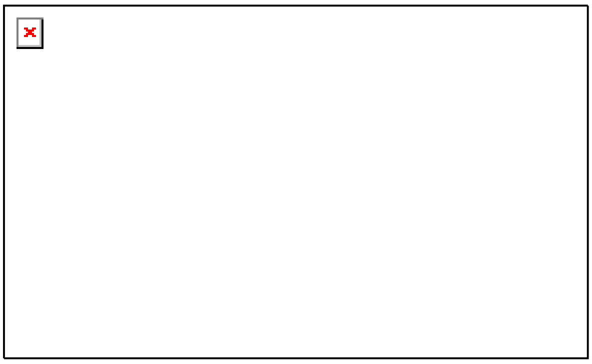

Fig. 9. **Calculations of the ground surface temperature history from the East-Vystupovichi-2 borehole thermogram.** The long-time warming from 1200 till 1800 seems to be unrealistic.

*Рис. 9***. Расчеты истории температуры поверхности Земли по термограмме скважины Восточно-Выступовичская-2.** Длительное потепление с 1200 до 1800 лет представляется нереальным.

The main factors, affecting the climate change in Belarus, are widely developed melioration of marched areas, deforestation and changing of gas content (CO_2, N_2O, CH_4, etc.) in the atmosphere caused by the combustion of different kinds of a fuel, changing the ground surface albedo, mainly in result of agricultural use of the land. A thermal contamination of rivers, ponds and lakes exists from factories, heat and electric plants. At present the area of melio-rated lands is around 3.3 thousand hectares, or 16% of the country. It includes 1.3 million hectares of marshed areas, which produces almost the same effect like the deforestation of 50% of the territory of Belarus The area of forests during the last 2.5 centuries was reduced by 2.2 times on average. It was even higher (3.7 times) during the Revolution and the Second World War years (Loginov, 1993). The deteriorated vast areas of the land were transformed in result of the peat excavation at 292.4 thousand hectares. At present the area c.a. 109,000 hectares is still in use for its production in Belarus (Klimat…, 1996).

Conclusions

Discussed results represent an attempt to reconstruct the history of paleoclimate in Belarus inferred from borehole thermograms. The most reliable results show the tendency of the ground surface temperature to increase within 0.5-1.0 ^{O}C after 50th years of our century. It agrees with the records of the oldest meteorological stations in Europe such as Vienna and Prague and averaged mean annual records from Belarussian stations. The quality of the available temperature-depth diagrams has permitted only to resolve 2-3 climatic events. Two main minima around 1750 and 1950 years are in agreement with results, obtained for other parts of Europe (Borehole..., 1994; Štulc et al., 1998). Some incoherency exsists between two groups of boreholes (Fig. 7a and b), they indicate that besides changes caused by the climate, there are some additional disturbances, their actual origin is still in question.

Some scatter in the amplitude of warming, derived from different thermograms, could be a result of the lack of thermal conductivity and diffusivity of rocks. Another reason could be attributed to the agricultural use of the land and related deforestation, though it is problematic to gather the relevant detailed information.

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ИЗМЕНЕНИЯ КЛИМАТА В БЕЛАРУСИ ПО ТЕРМОГРАММАМ СКВАЖИН

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Измерение температур в скважинах было предпринято в Беларуси в течение ряда лет как в мелких, так и глубоких скважинах, главным образом, для изучения теплового потока. Термограммы, зарегистрированные при условиях теплового равновесия в скважинах в пределах основных тектонических структур страны, иногда имеют как вогнутую, так и выпуклую форму. Они несут следы палеотемпературных изменений, имевших место на земной поверхности. Температурные флуктуации распространяются вглубь при затухающей амплитуде и фазовом сдвиге, которые зависят от глубины. Несколько диаграмм температура-глубина без заметного влияния циркуляции подземных вод были отобраны для палеотемпературной реконструкции. Первые оценки показывают, что имело место потепление земной поверхности на 0,5-1 °С в течение последних 200-300 лет. Надежность палеоклиматического сигнала, полученного из термограмм, зависит от локальных условий, например, циркуляции подземных вод, сельскохозяйственного эффекта из-за культивации земель, но отсутствуют детальные данные как по истории сельскохозяйственного освоения земель, прилегающих к изучаемым скважинам, так и о скорости фильтрации вод в окрестности выбранных скважин.

ЗМЕНЫ КЛІМАТУ Ў БЕЛАРУСІ ПА ТЭРМАГРАМАХ СВІДРАВІН

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Вымярэнні тэмператур у свідравінах былі выкананы ў Беларусі на працягу шэрагу гадоў як у мелкіх, так і глыбокіх свідравінах, галоўным чынам, для вывучэння цеплавога струменю. Тэрмаграмы, зарэгістраваныя пры ўмовах цеплавой раўнавагі ў свідравінах у межах асноўных тэктанічных структур

краіны, часам маюць як увагнутую, так и выпуклую форму. Яны нясуць сляды палеатэмпературных змен, якія мелі месца на зямной паверхні. Тэмпературныя флуктуацыі распаўсюджваюцца ў глыбіню пры затухаючай амплітудзе і фазавай затрымцы, якія залежаць ад глыбіні. Некалькі дыяграм тэмпература-глыбіня без прыметнага ўплыву цыркуляцыі падземных вод былі адабраны для палеатэмпературнай рэканструкцыі. Першыя ацэнкі паказваюць, што мела месца пацяпленне зямной паверхні на 0,5-1 °С на працягу апошніх 200-300 гадоў. Надзейнасць палеакліматычнага сігналу, атрыманага з тэрмаграм, залежыць ад лакальных умоў, напрыклад, цыркуляцыі падземных вод, сельскагаспадарчага эфекту, выкліканага культывацыяй зямель, але адсутнічаюць дэтальныя дадзеныя як па гісторыі сельскагаспадарчага выкарыстання зямель, прылягаючых да вывучаемых свідравін, так і па скорасці фільтрацыі вод у наваколлі выбраных свідравін.